

EnergyPlus: Energy Simulation Program

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Various building energy simulation programs developed around the world are reaching maturity. Many use simulation methods (and even code) that originated in the 1960s. Without substantial redesign and restructuring of the programs, continuing to expand their capabilities has become difficult, time-consuming, and prohibitively expensive. However, phenomenal advances in analysis methods and computational power have increased the opportunity for significant improvements in the flexibility and comprehensiveness of these tools.

The U.S. Department of Energy (DOE) began planning for a new generation of simulation tools in 1995 using a three-step process:

- Create an inventory of existing DOE-sponsored tools
- Sponsor workshops to get recommendations from users and developers about needs in energy simulation, and
- Define new generation tools based on the recommendations from the workshops and experience in developing BLAST [BLA] and DOE-2 [WIN].

Three organizations formed the initial development team: Lawrence Berkeley National Laboratory (LBNL)—developers of DOE's DOE-2 program (Winkelmann et al. 1993)—and U.S. Army Construction Engineering Laboratory (CERL) and the University of Illinois (UI)—developers of DOD's BLAST program [BLA]. This article focuses on the structure, features, and capabilities of EnergyPlus.

What is EnergyPlus?

EnergyPlus is a new building performance simulation program that combines the best capabilities and features from BLAST and DOE-2 along with new capabilities. EnergyPlus comprises completely new code written in Fortran 90. It is primarily a simulation engine—there is no formal user interface. Both BLAST and DOE-2 have many user interfaces developed by independent third-party developers. We have invited these same developers to work on graphical user interfaces for EnergyPlus.

Modular Code

One of the main goals for EnergyPlus is to create a well-organized, modular structure that facilitates adding features and links to other programs. We decided to select Fortran 90 as the programming language for EnergyPlus because Fortran 90:-

- is a modern, modular language with good compilers on many platforms.
- allows C-like data structures and mixed language modules.
- provides structure that begins to be object-based.

- allows long variable names (up to 32 characters).
- provides backward compatibility during the development process.

We began working on EnergyPlus by modularizing (restructuring) code from the heat balance engine in IBLAST, a research version of BLAST with integrated loads and HVAC calculation [TAY]. Normally, such restructuring would result in major rewrites involving a long development period, and extensive testing to ensure the new code performs as intended. To avoid this problem, we devised a process we call "Evolutionary Reengineering (ER)" that incrementally moves the program from old unstructured code to new modular code by incorporating new code with old. Throughout the process, existing code still works with user input data, and is extended to generate parameters needed by the new code modules. In this way the new modules can be verified without having to completely replace the entire functional capability of the old program with new code before it can be tested. As the process proceeds, old routines are replaced by new routines and data structures. This makes the transition evolutionary and permits a smooth transition with a greater capability for verification testing. By the time we had achieved an alpha version, all the old code had been replaced.

EnergyPlus Structure

In the next generation simulation tools workshops there was strong consensus that a more flexible and robust tool with additional capabilities is needed. Recurrent themes for energy simulation needs throughout the workshops were design, environment, economics, and occupant comfort and safety. Designers need tools that provide answers to specific questions during design. They want tools that provide the highest level of simulation accuracy possible with a reasonable level of detail but don't get in the user's way. One of the highest priorities was an integrated (simultaneous) simulation for accurate temperature and comfort prediction.

In response to these findings, we decided that integrated simulation should be the underlying concept for EnergyPlus—loads calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module during the same time step. The building systems simulation module, with a variable time step (down to seconds), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary.

By using an integrated solution technique in EnergyPlus, the most serious deficiency of the BLAST and DOE-2 sequential simulations can be solved—inaccurate space temperature prediction due to no feedback from the HVAC module to the loads calculations. Accurate prediction of space temperatures is crucial to energy efficient system engineering—evaluation of system and plant size, and occupant comfort and health all require accurate space temperature prediction.

Integrated simulation also allows users to evaluate a number of processes that neither BLAST nor DOE-2 can simulate well. Some of the more important include:

- Realistic system controls.
- Interzone airflow.
- Radiant heating and cooling systems.
- Moisture adsorption and desorption in building elements.

Figure 1 shows the overall program structure and the three basic components: Simulation Manager, Heat Balance Simulation module, and Building Systems Simulation module.

The Simulation Manager controls the entire simulation process, the Heat Balance Simulation module calculates thermal and mass loads, and the Building Systems Simulation Manager handles communication between the heat balance engine and the HVAC water and air loops and their attached components (coils, boilers, chillers, pumps, fans, etc.). We replaced the hardwired "template" systems (VAV, Constant Volume Reheat, etc.) of DOE-2 and BLAST with user-configurable heating and cooling equipment components. As starting points for users, we have created input file templates to describe the more popular system types from DOE-2 and BLAST. This gives users much more flexibility in matching their simulation to the actual system configurations. The Building Systems Simulation Manager also manages data communication between the building systems (HVAC, electrical) modules, building description (input data), and calculation results (output data). A comparison of major features and capabilities of EnergyPlus, BLAST, IBLAST, and DOE-2 are shown in Tables 1-3.

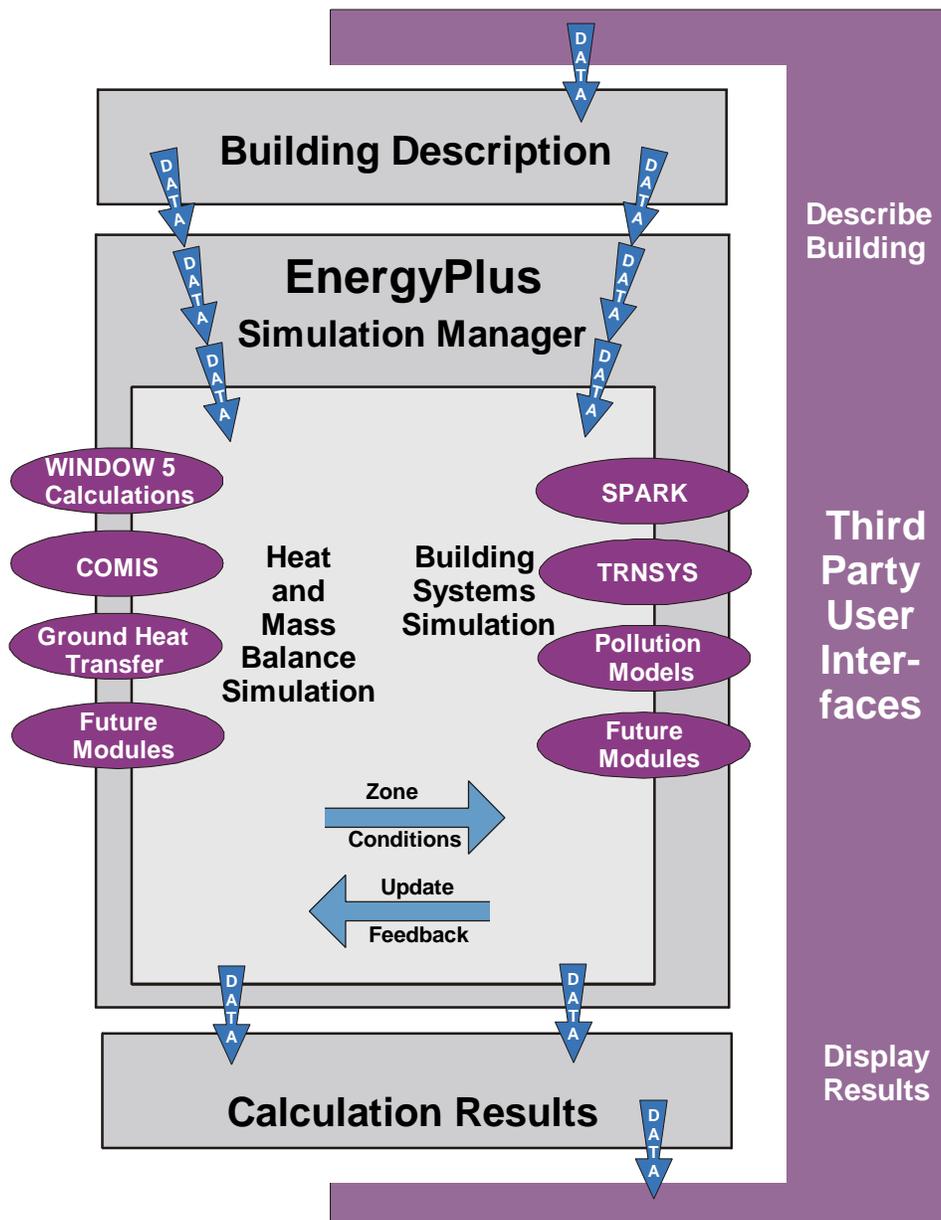


Figure 1: Overall EnergyPlus structure.

Simulation Management

At the outermost program level, the Simulation Manager controls the interactions between all simulation modules from a sub-hour level up through the user-selected time step and simulation period—day, month, season, year or several years. The Simulation Manager instructs simulation modules to take actions such as initialize, simulate, record keep, or report.

Having a Simulation Manager provides several benefits:

- Major simulation loops are contained in a single module.
- Modules are self-contained and more object-based.
- New modules can be added easily.

Heat & Mass Balance Calculation

The underlying building thermal zone calculation method in EnergyPlus is a heat balance model in which room air is modeled as well stirred with uniform temperature throughout. (The modular structure of EnergyPlus allows more detailed room air convection calculations—such as CFD or zonal methods—to be included later in the program.) It also is assumed that room surfaces (walls, windows, ceilings, and floors) have:

- Uniform surface temperatures.
- Uniform long and short wave irradiation.
- Diffuse radiating and reflecting surfaces.
- Internal heat conduction.

Table 1: Comparison of general features and capabilities.

| General Features | DOE-2 | BLAST | IBLAST | EnergyPlus |
|---|-------|-------|--------|------------|
| Integrated, Simultaneous Solution <ul style="list-style-type: none"> ▪ Integrated loads/systems/plant ▪ Iterative solution ▪ Tight coupling | No | No | Yes | Yes |
| Multiple Time Step Approach <ul style="list-style-type: none"> ▪ User-defined time step for interaction between zones and environment (15-minute default) ▪ Variable time step for interactions between zone air mass and HVAC system (> minute) | No | No | Yes | Yes |
| Input Functions <ul style="list-style-type: none"> ▪ Users can modify code w/o recompiling | Yes | No | No | Yes |
| New Reporting Mechanism <ul style="list-style-type: none"> ▪ Standard reports ▪ User-definable reports with graphics | No | No | No | Yes |

Figure 2 shows the structure of the EnergyPlus integrated solution manager that manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The Surface Heat Balance Module simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapor) effects. The Air Mass Balance Module deals with various mass streams such as ventilation and exhaust air, and infiltration. It

accounts for thermal mass of zone air and evaluates direct convective heat gains. It is through this module that we are connecting to COMIS for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations [HUA].

In addition to the basic heat balance engine from IBLAST, we have created three new modules based on capabilities from DOE-2: daylighting simulation, WINDOW 4-based window calculation, and anisotropic sky. The daylighting module calculates hourly interior daylight illuminance, window glare, glare control, electric lighting controls, and calculates electric lighting reduction for the heat balance module.

The window module incorporates algorithms from WINDOW 5—accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users can enter a layer-by-layer window description or choose windows from the library (conventional, reflective, low-E, gas fill). Sun control can be modeled with pull-down shades, blinds or electrochromic glazing.

The sky model includes non-isotropic radiance and luminance distribution of the sky based on the empirical model [PER1, PER2] as a function of sun position and cloud cover. This non-uniform radiance distribution improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs).

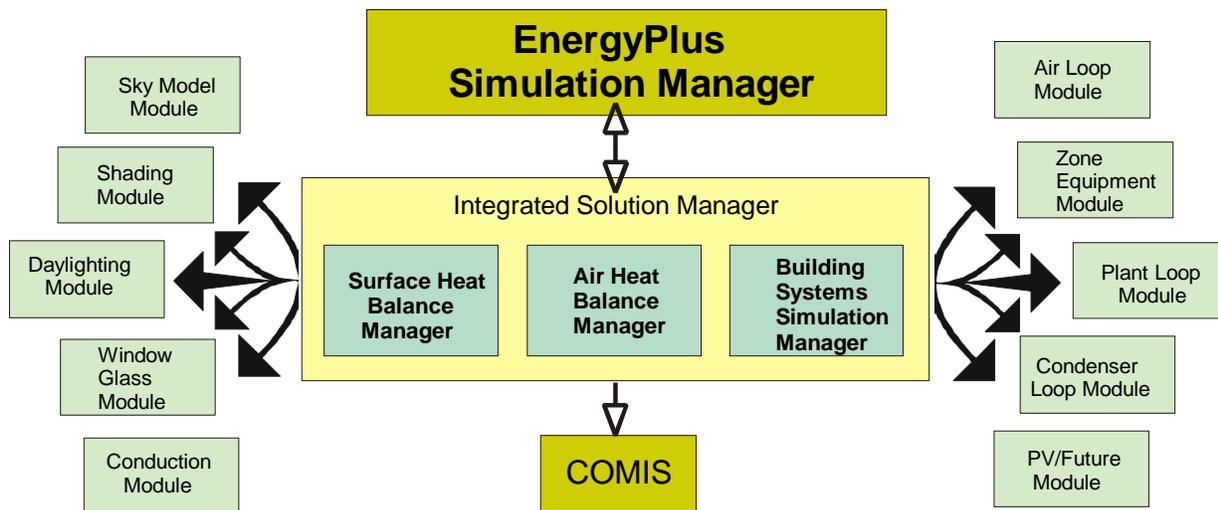


Figure 2: Integrated Simulation Manager.

Several other modules have been reengineered for inclusion in EnergyPlus: solar shading from BLAST and conduction transfer function (CTF) calculations from IBLAST. The major enhancements of the IBLAST (and EnergyPlus) heat balance engine over BLAST include mass transfer and radiant heating and cooling. The mass transfer capability within EnergyPlus allows fundamental, layer-by-layer solution for mass transfer through surfaces and a mass balance for zone air similar to the air heat balance. The radiant heating and cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations. This provides a means for improved modeling and control capabilities for the new building systems simulation manager.

With the support of the Gas Research Institute and Florida Solar Energy Center, we are incorporating a simplified moisture model known as Effective Moisture Penetration Depth (EMPD) to estimate moisture interactions among the space air and interior surfaces and furnishings. EMPD is useful for estimating impacts associated with moisture where detailed internal geometry and/or detailed material properties are not readily available.

Another important feature of the EnergyPlus heat balance engine is that it is essentially identical in functionality to the Loads Toolkit being developed by UI under ASHRAE RP-987. UI is developing both the Loads Toolkit and the EnergyPlus heat and mass balance engine and is using the programming standard developed in the EnergyPlus project to produce the Loads Toolkit. Both projects benefit: modularization efforts started by EnergyPlus will be useful in the Loads Toolkit and new component models developed for the Loads Toolkit will enhance EnergyPlus. Strand et al [STR] report on the implementation of the heat balance technique in EnergyPlus.

Building Systems Simulation Manager

After the Heat Balance Manager completes simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates zone-air conditions. EnergyPlus does not use the sequential simulation method (first building loads, then distribution system, and then plant) found in DOE-2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Instead, we designed the Building Systems Simulation Manager with three objectives: fully integrated simulation of loads, systems, and plant; modular; extensible.

Integrated simulation allows capacity limits to be modeled more realistically and provides tighter coupling between the air- and water-side of the system and plant. Modularity is maintained at both the component and system level. This eases adding new components and flexibly modeling system configurations and, at the system level, equipment and systems are clearly connected to zone models in the heat balance manager. To implement these concepts, we use loops throughout the Building Systems Simulation Manager—primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings; later, EnergyPlus will simulate head and thermal losses that occur as fluid moves in each loop.

The air loop simulates air transport, conditioning and mixing, and includes supply and return fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment. Zone equipment includes diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioning, fan coil, water-to-air heat pump, air-to-air heat pump), high temperature radiant/convective units (baseboard, radiators) and low temperature radiant panels. Users can specify more than one equipment type for a zone. However, equipment must be listed in the order it will be used to meet zone heating and cooling demand.

The air loop is solved iteratively at each time step, not a single-pass calculation as in DOE-2 and BLAST. In order to specify equipment connections to a loop, nodes are defined at key locations around the loop with each node assigned a unique numeric identifier. Node identifiers store loop state variables and set-point information for that location in the loop. We use an iterative solution technique to solve for unknown state variables along with control equation representations. These representations connect the set points at one node with the control function of a component, such as fan damper position and cooling coil water flow rate. In this scheme, all the loop components are simulated first, and then the control equations are updated using explicit finite difference. This procedure continues until the simulation converges.

There are two water loops for HVAC plant equipment—a primary loop (for supply equipment such as boilers, chillers, thermal storage, and heat pumps) and a secondary loop (for heat rejection equipment such as cooling towers and condensers). Equipment is specified by type (gas-fired boiler, open drive centrifugal chiller) and its operating characteristics. In the first release of EnergyPlus we are supporting curve-based equipment models derived from manufacturer performance data (such

as in BLAST and DOE-2). However, because of the modular code, it will be easy for developers to add other types of models.

As in the air loop, the primary and secondary plant loops use explicit nodes to connect equipment to each loop. Connections between the air loop and zone equipment and the primary and secondary loops are made through the node data structure and must be explicitly defined in the input file.

A similar loop approach is proposed for a new electrical loop for simulating electrical systems—supply (utility, photovoltaic modules, and fuel cells), demand (plug loads, lighting, and other electrical loads), and measurement (meters). In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK, a new equation-based simulation tool. SPARK is a better solver for complex iterative problems and is currently in final beta testing. A library of HVAC components has been created for SPARK. As mentioned earlier, EnergyPlus users will have input file templates for many of the more popular system types to use as starting points but developers and advanced users will be able to build complex new HVAC models with SPARK. Fisher et al (1999) provide more information on the EnergyPlus loop-based simulation.

Table 2: Comparisons of loads features and capabilities.

| General Features | DOE-2 | BLAST | IBLAST | EnergyPlus |
|--|--------------|--------------|---------------|-------------------|
| Heat Balance Calculation | No | Yes | Yes | Yes |
| <ul style="list-style-type: none"> ▪ Simultaneous calculation of radiation and convection processes each time step | | | | |
| Interior Surface Convection | No | Yes | Yes | Yes |
| <ul style="list-style-type: none"> ▪ Dependent on temperature and air flow ▪ Internal thermal mass | Yes | Yes | Yes | Yes |
| Moisture Adsorption/Desorption | No | No | Yes | Yes |
| <ul style="list-style-type: none"> ▪ Combined heat and mass transfer in building envelopes | | | | |
| Thermal Comfort | No | Yes | Yes | Yes |
| <ul style="list-style-type: none"> ▪ Human comfort model based on an activity, inside dry bulb, humidity and radiation | | | | |
| Anisotropic Sky Model | Yes | No | No | Yes |
| <ul style="list-style-type: none"> ▪ Sky radiance depends on sun position for better calculation of diffuse solar radiation on tilted surfaces | | | | |
| Advanced Fenestration Calculations | Yes | No | No | Yes |
| <ul style="list-style-type: none"> ▪ Controllable window blinds ▪ Electrochromic glazing | | | | |
| WINDOW 5 Calculations | Yes | Yes | Yes | Yes |
| <ul style="list-style-type: none"> ▪ More than 200 window types - conventional, reflective, low-E, gas-fill, electrochromic ▪ User-defined using WINDOW 5 | | | | |
| Daylighting Illumination and Controls | Yes | No | No | Yes |
| <ul style="list-style-type: none"> ▪ Interior illuminance from windows and skylights ▪ Step, dimming, on/off luminaire controls ▪ Glare simulation and control ▪ Effects of dimming on heating and cooling | | | | |

Input, Output, & Weather Data

Instead of user readability, we designed the EnergyPlus input and output data files for easy maintenance and expansion. We chose to keep the input file format simple in order to accept simulation input data from other sources such as CADD programs, and preprocessors similar to those written for BLAST and DOE-2. An EnergyPlus input file is not intended to be the main interface for typical end-users. We expect most users will use EnergyPlus through an interface from a third-party developer. To make it easy for current DOE-2 and BLAST users to move to EnergyPlus, the team has written utilities that convert BLAST and DOE-2 input requirements to the new EnergyPlus input.

Table 3: Comparisons of HVAC features and capabilities.

| HVAC Systems and Equipment Feature | DOE-2 | BLAST | IBLAST | EnergyPlus |
|--|--------------|--------------|---------------|-------------------|
| Fluid Loops <ul style="list-style-type: none"> ▪ Connect primary equipment and coil ▪ Hot water loops, chilled water and condenser Loops, refrigerant loops | No | No | No | Yes |
| Air Loops <ul style="list-style-type: none"> ▪ Connect fans, coil, mixing boxes, zones | No | No | No | Yes |
| Hardwired Template HVAC Systems | Yes | Yes | Yes | No |
| User-configurable HVAC Systems | No | No | No | Yes |
| High-Temperature Radiant Heating <ul style="list-style-type: none"> ▪ Gas/electric heaters and wall radiators | No | Yes | No | Yes |
| Low-temperature Radiant Heating/Cooling <ul style="list-style-type: none"> ▪ Heated floor/ceiling ▪ Cooled ceiling | No | No | Yes | Yes |
| Atmospheric Pollution Calculation <ul style="list-style-type: none"> ▪ CO₂, SO_x, NO_x, CO, particulate matter and hydrocarbon production ▪ On-site and at power plant ▪ Calculate reductions in greenhouse gasses | Yes | Yes | No | Yes |
| SPARK Link | No | No | No | Yes |
| TRNSYS Link | No | No | No | Yes |

During a simulation, EnergyPlus saves results for each time step in an output data structure. The user selects the heat balance time step (15-minute default). The building system simulation may proceed at the heat balance time step or at smaller time steps in order to reach stability. The EnergyPlus output processor produces results in a simple variable-based format that can easily be read by post-processing programs.

The other major data input is weather. Rather than a binary file created by a separate weather processor, again we use a simple comma-separated, text-based format, similar to the input data and output data files. The weather data format includes basic location information in the first eight lines: location (name, state/province/region, country), data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, and typical and extreme periods. The data contain much of the same data in the TMY2 weather data set. EnergyPlus does not require a full year (8,760 or 8,784 hours) for its weather files. In fact, EnergyPlus allows and reads subsets of years and even sub-hourly (5 minute, 15 minute) data

because the weather format includes a "minutes" field. EnergyPlus comes with a utility that reads standard weather service file types such as TD1440 and DATSAV2 and newer "typical year" weather files such as TMY2 and WYEC2. A detailed review of the EnergyPlus weather format is provided in [CRA].

In summary, all the data files associated with EnergyPlus—input, output, and weather—have simple, self-contained formats which can be easily read and interpreted by other programs—spreadsheets, databases, or custom programs.

Adding A New Module

One of the main goals for EnergyPlus is to make it easy for developers to add new features and modules. The process is relatively simple. First, a developer defines a new module with model parameters and equations, specialized coefficients, and data needed. A developer then finds the "plug-in" point—where the module would be called within EnergyPlus. Next, the developer writes the module (using the EnergyPlus programming standard), breaking the simulation tasks into modules. Finally, the developer writes new input file syntax based on the input needed for the module, determines what variables will be available for output processing and uses EnergyPlus internal service routines to get the input and produce any output.

Release 1.0 and Beyond

The first working version of EnergyPlus, an alpha version, was completed in Dec. 1998 for internal testing by the team. We plan to release a series of EnergyPlus beta versions with increasing capabilities for testing by outside developers and users beginning in late 1999. Currently, we anticipate releasing Version 1.0 of EnergyPlus by early 2001.

In mid-2000 we will begin planning for Version 2.0 of EnergyPlus based on new features suggested by users, developers and the team. Working with a coordinating group of users and developers, we will then select the features and capabilities for that release. We plan to release updates to EnergyPlus on a regular, 18-month release cycle. Some new features already under development are links to TRNSYS and SPARK, a connection to the COMIS airflow program, improved ground heat transfer, electrical system simulation, and solar thermal and photovoltaic modules.

Summary

EnergyPlus is new energy simulation program that builds on the strengths of both BLAST and DOE-2 and includes many new simulation capabilities. Features include:

- Heat balance load calculations.
- Integrated loads, system and plant calculations in same time step.
- User-configurable HVAC system description.
- Modular structure to make it easy for other developers to add new simulation modules.
- Simple input and output data formats to facilitate graphical front-end development.

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Web Resources

1. **Building Energy Tools Directory**, a directory of information on more than 190 energy tools from around the world - www.eren.doe.gov/buildings/tools_directory/
2. **Next-Generation Simulation Workshops**, description of the results from two workshops on needs for new energy simulation tools - www.eren.doe.gov/buildings/energy_tools/workshops.htm
3. **EnergyPlus**, up-to-date information on the current status of EnergyPlus and working with the team, and documentation such as input data structure, output data structure, and licensing opportunities - www.eren.doe.gov/buildings/energy_tools/energyplus.htm

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